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13. ABSTRACT (Maximum 200 words) The broad goal of the project is to investigate techniques to minimize the soaring cost of software evolution, focusing on component-based systems where predictable behavior and performance are important. Key research results include techniques for reusable component and pattern design, formal specification of behavior and performance, modular verification of behavior and performance correctness, and principles for contract-checking components. Languages and tools that incorporate these findings are key technology transfer results. Key educational results include a formal approach and materials for teaching component-based software engineering at the graduate and undergraduate levels in Computer Science, and statistical evaluation of the approach.				
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## Table of Contents

A. Problem Statement	3
B. Summary of Key Results	3
C. List of Publications	5
D. Scientific Personnel	12

## A. Problem Statement

The overall problem is to minimize the soaring cost of software evolution in the context of component-based systems, in particular, those systems where predictable behavior and performance are fundamental concerns. While the problem exists in the case of legacy systems and systems especially designed for predictability and evolution, the focus of the project is on designing predictable systems to evolve gracefully. Goals include investigation of research techniques, development of tools, and identification of education and technology transfer activities to minimize the cost of evolution. The proposed techniques should minimize the cost for understanding, reasoning, reuse and adaptation during development and evolution.

## Summary of Key Results

The central results of the project are listed are aimed at addressing the above goals. They include:

- Reusable software component and pattern design principles;
- Modular verification of behavior, including the need for abstraction relations;
- Principles and practical techniques for contract-checking components;
- Formal specification of performance and modular verification of performance correctness;
- Languages and tools for predictable component-based software development and evolution;
- A formal approach to component-based software engineering: education and statistical evaluation.

Follow-up research and educational work are funded by National Science Foundation grants, including an Information Technology Research (ITR) grant in 2001. The results from the project have been widely disseminated in over 50 publications. Section C of the report contains a listing of publications during each year of the project. Journal publications have appeared in practical and theoretical places such as *IEEE Transactions on Software Engineering*, *John Wiley Software – Practice and Experience*, and *Springer-Verlag Formal Aspects of Computing*. Conference publications include ones in the *International Conference on Software Engineering (ICSE)*, *International Conference on Software Reuse (ICSR)*, *Symposium on Software Reuse*, *International Symposium on Software Reliability Engineering*, and *ACM SIGCSE Technical Symposium on Computer Science Education*. An edited book on *Foundations of Component-Based Systems* published by Cambridge University Press in 2000 contains articles from leading software engineering researchers and practitioners, and it has benefited from this project.

It is important to emphasize that the impact of this project will remain. Follow-up research and educational work have been funded by National Science Foundation grants, including an Information Technology Research (ITR) grant in 2001. At least three more journal submissions on performance analysis, parameter passing of objects using swapping, and contract-checking principles are planned in the near future. These planned

submissions are *not* included in this report.

The project has been instrumental in continued development and refinement of RESOLVE as a research and educational vehicle for component-based software engineering. During the course of the project, a variety of practical component development issues and foundational formal specification questions in software engineering have been addressed. The project has laid the foundation for the RESOLVE software composition workbench – an environment for predictable component-based software construction – in collaboration with investigators at The Ohio State University. Researchers have developed a variety of tools, including compilers, translators, editors, and an interactive environment. These tools are at varying levels of maturity and sophistication. They have been demonstrated at DARPA meetings and conferences. The tools will serve as our principal vehicle for transitioning the results from the project to academia, industry, and the U. S. defense program. They are available at <http://www.cs.clemson.edu/~resolve>.

Four Ph. D. dissertations and seven M. S. project reports and theses have also resulted from the project, in addition to several education-oriented materials and publications. These results and some of our efforts in technology transition are document in Section IV. Together with NSF and Department of Education grants, this project has facilitated introduction of a formal approach to component-based software development in undergraduate Computer Science education. The approach and positive results from statistical evaluation of student attitudes and learning have been published.

## C. List of Publications

### C. 1 Topic Area Dissemination Publications

1. M. Sitaraman, "Session Overview: Compositional Reasoning," *Proceedings of the Fourth ICSE Workshop on Component-Based Software Engineering (CBSE4)*, Toronto, Canada, May 2001, 45-46.
2. *Proceedings of the ACM OOPSLA Workshop on Specification and Verification of Component-Based Systems*, Eds. G. T. Leavens, M. Sitaraman, and D. Giannakopoulou, Tampa, FL, October 2001; available at [www.cs.iastate.edu/~leavens](http://www.cs.iastate.edu/~leavens).
3. M. Sitaraman, S. Atkinson, J-M. Debaud, F. Maymir-Ducharme, "Panel: Where Should We Invest for Reusability to Live Up to Its Potential?," *Proceedings of the ACM SIGSOFT Symposium on Software Reuse (SSR)*, Toronto, Canada, May 2001.
4. *Foundations of Component-Based Systems*, Eds. G. T. Leavens and M. Sitaraman, Cambridge University Press, February 2000.
5. Mili and S. Atkinson, "Software Libraries," *Encyclopedia of Electrical and Electronics Engineering*, Ed. J. G. Webster, John Wiley and Sons, 2000.
6. M. Sitaraman, "Software Reusability," *Wiley Encyclopaedia of Electrical and Electronics Engineering*, Vol. 19, Ed. J. G. Webster, John Wiley & Sons, 1999, pp. 578-590.
7. M. Sitaraman, panel moderator, "Software Reuse Research: Contribution, Problems and Non-Problems," *Proceedings of the ACM SIGSOFT Symposium on Software Reuse*, ACM Press, May 1999, pp.178-180.
8. G. T. Leavens, O. Nierstrache, M. Sitaraman, "1997 Workshop on Foundations of Component-Based Systems, *ACM SIGSOFT Software Engineering Notes* 23, No. 1, January 1998, pp. 38-41.
9. M. Sitaraman and S. H. Zweben, "Guest Editorial: Introduction to the Special Section on Software Reuse," *IEEE Transactions on Software Engineering* 23, No. 2, February 1997, 1-2.
10. *Proceedings of the Workshop on Foundations of Component-Based Systems*, Eds. G. T. Leavens and M. Sitaraman, Zurich, Switzerland, September 1997; available at [www.cs.iastate.edu/~leavens](http://www.cs.iastate.edu/~leavens).

## C.2 Research Publications

11. M. Aronszajn, S. Atkinson, G. Kulczycki, and M. Sitaraman, "A System for Predictable Component-Based Software Construction," *High Integrity Software*, Eds. V. Winter and S. Bhattacharya, Kluwer Academic, April 2001.
12. M. Sitaraman, G. Kulczycki, J. Krone, W. F. Ogden, and A. L. N. Reddy, "Performance Specification of Software Components," *Proceedings of the ACM SIGSOFT Symposium on Software Reuse (SSR)*, Toronto, Canada, May 2001.
13. M. Sitaraman, "Compositional Performance Reasoning," *Proceedings of the Fourth ICSE Workshop on Component-Based Software Engineering (CBSE4)*, Toronto, Canada, May 2001, 98-101.
14. J. Krone, W. F. Ogden, and M. Sitaraman, "Modular Verification of Performance Correctness," *Proceedings of the ACM OOPSLA Workshop on Specification and Verification of Component-Based Systems*, October 2001; available at [www.cs.iastate.edu/~leavens](http://www.cs.iastate.edu/~leavens).
15. G. Kulczycki, "Type Handling in a Fully-Integrated Programming and Specification Language," *Proceedings of the ACM OOPSLA Workshop on Specification and Verification of Component-Based Systems*, October 2001; available at [www.cs.iastate.edu/~leavens](http://www.cs.iastate.edu/~leavens).
16. S. Yacoub and H. Ammar, "Towards Pattern Oriented Frameworks," *Journal of Object Oriented Programming*, 12(8):25-35, January 2000.
17. M. Sitaraman, S. Atkinson, G. Kulczyski, B. W. Weide, T. J. Long, P. Bucci, W. Heym, S. Pike, and J. Hollingsworth, "Reasoning about Software-Component Behavior," *Proceedings of the Sixth International Conference on Software Reuse*, Springer Verlag, Vienna, Austria, June 2000, 266-283.
18. S. Yacoub, H. Ammar, and A. Mili, "Constructional Design Patterns as Reusable Components," *Proceedings of the Sixth International Conference on Software Reuse*, Springer-Verlag, Vienna, Austria, June 2000.
19. M. Sitaraman, B. W. Weide, T. J. Long, and W. F. Ogden, "A Data Abstraction Alternative to Data Structure Algorithm Modularization," *Generic Programming*, Eds. M. Jazayeri, R. J. K. Loos, and D. Musser, LNCS 1766, Springer-Verlag, June 2000, 102-113.
20. S. Yacoub, H. Xue, and H. Ammar, "Automating the Development of Pattern-Oriented Designs for Application Specific Software Systems," *Proceedings of the*

*Third IEEE Symposium on Application-Specific Systems and Software Engineering Technology*, Richardson, Texas USA, March 2000.

21. S. Yacoub and H. Ammar, "A Matrix-Based Approach to Measure Coupling in Object-Oriented Designs," *Journal of Object Oriented Programming*, 2000.
22. S. Yacoub and H. Ammar, "Finite State Machine Patterns," *Chapter 19 in Pattern Languages of Program Design 4*, Eds. N. Harrison, B. Foote, and H. Rohnert, Addison Wesley 1999, pp. 413-440.
23. S. Atkinson, "(Unreasonable Software) Reuse is Unreasonable (Software Reuse)", *Procs. Ninth Annual Workshop on Software Reuse*, Austin, TX, January 1999, 5 pages.
24. M. Sitaraman, "Why Neither Formal Methods Nor Java Can Do It Alone", *Procs. Ninth Annual Workshop on Software Reuse*, Austin, Texas, January 1999, 5 pages.
25. S. Yacoub and H. Ammar, "Measuring Design Quality of Object-Oriented Design Frameworks," *Proceedings of the First International Software Assurance Certification Conference*, Washington D.C., March 1999.
26. S. Yacoub and H. Ammar, "The Development of a Client/Server Architecture for Standardized Medical Application Network Services," *Proceedings of the IEEE Symposium on Application Specific Software Engineering Technology (ASSET '99)*, Dallas, Texas, March 1999, pp2-9.
27. S. Yacoub and H. Ammar, "Tool Support for Developing Pattern-Oriented Architectures," *Proceedings of the First Symposium on Reusable Architectures and Components for Developing Distributed Information Systems*, Orlando, Florida, August 1999, pp. 665-670.
28. C. Fuhrman, N. Solderitsch, S. Yacoub, and H. Ammar, "An Integrated Tool Environment for DoD Product Line Engineering", *Proceedings of the First Symposium on Reusable Architectures and Components for Developing Distributed Information Systems*, Orlando, Florida, August 1999, pp 618-620.
29. Mili, S. Yacoub, E. Addy, and H. Mili, "Toward an Engineering Discipline of Software Reuse," *IEEE Software*, 16(5):22-31, September/October 1999.
30. S. Yacoub, B. Cukic, and H. Ammar, "A Component-Based Approach to Reliability Analysis of Distributed Software Systems," *Proceedings of the Eighteenth IEEE Symposium On Reliable Distributed Systems*, Lausanne, Switzerland, October 1999, pp. 158-167.
31. S. Yacoub, B. Cukic, and H. Ammar, "Scenario-based Reliability Analysis of Component-Based Software," *Proceedings of the Tenth International Symposium*



- on Software Reliability Engineering*, Boca Raton, Florida USA, November 1999, pp. 22-31
32. S. Yacoub, H. Ammar, and T. Robinson, "Dynamic Metrics for Object Oriented Designs," *Proceedings of the Sixth International Symposium on Software Metrics*, Boca Raton, Florida USA, November 1999, pp. 50-61.
  33. S. Yacoub, and H. Ammar, "An Object-oriented Framework for Feedback Control Applications", *Proceedings of Application Specific Software Engineering Technology ASSET'98*, IEEE Computer Society, Dallas, Texas, March 1998, pp134-139.
  34. S. Yacoub and H. Ammar, "Finite State Machine Patterns", *Procs. Third European Conference on Pattern Languages of Programming and Computing*, Irsee, Germany, July 1998.
  35. S. Yacoub and H. Ammar, "A Pattern Language of Statecharts", *Procs. Fifth Annual Conference on the Pattern Languages of Programs*, Allerton Park, Illinois, August 1998.
  36. S. Edwards, G. Shakir, M. Sitaraman, B. W. Weide, and J. Hollingsworth, "A Framework for Detecting Interface Violations in Component-Based Software," *Procs. Fifth International Conference on Software Reuse*, IEEE Computer Society Press, Victoria, Canada, June 1998.
  37. S. Yacoub and H. H. Ammar, "A Technique to Measure Coupling in Object-Oriented Designs", *Procs. Ninth International Conference on Software Reliability Engineering, ISSRE'98*, Industrial Track, Paderborn, Germany, Nov 1998, pp95-102
  38. B. Cukic, H. H. Ammar, and K. Lateef "Identifying High-Risk Scenarios of Complex Systems using Input Domain Partitioning," *Procs. Ninth International Conference on Software Reliability Engineering, ISSRE'98*, IEEE Computer Soc., Paderborn, Germany, Nov 1998.
  39. S. Sreerama, D. Fleming, and M. Sitaraman, "Graceful Object-Based Performance Evolution," *Software — Practice and Experience*, January 1997, 111-122.
  40. M. Sitaraman, B. W. Weide, and W. F. Ogden, "On the Practical Need for Abstraction Relations to Verify Abstract Data Type Representations," *IEEE Transactions on Software Engineering* 23, No. 3, March 1997, 157-170.
  41. M. Sitaraman, "Conventional Domain Analysis Limits Reusability", *Procs.*

*Eighth Annual Workshop on Software Reuse*, Columbus, Ohio, March 1997, 4 pages.

42. D. Fleming, M. Sitaraman, and S. Sreerama, "A Performance Criterion for Object Interface Design," *Journal of Object-Oriented Programming*, July/August 1997, 52-63.
43. V. Mogulothu, H. H. Ammar, K. Lateef, T. Nikzadeh, and Z. Miao, "Performability Analysis of the Commanding Component of NASA's Earth Observing System," *Proceedings of the ISCA Tenth International Conference on Parallel and Distributed Computing Systems*, New Orleans, LA, October 1997.
44. H. H. Ammar, T. Nikzadeh, and J. B. Dugan, "A Methodology for Risk Assessment of Functional Specification of Software Systems Using Colored Petri Nets," *IEEE Computer Society Proceedings of the Fourth International Software Metrics Symposium*, Albuquerque, New Mexico, November 1997, 108-117.
45. H. H. Ammar, T. Nikzadeh, and J. B. Dugan, "An Example of Risk Assessment of Software System Specifications," *IEEE Computer Society Proceedings of the Eighth International Symposium on Software Reliability Engineering*, Albuquerque, New Mexico, November 1997, 156-167.

### **C.3 Education and Technology Transfer Publications**

46. Sitaraman, M., Long, T.J., Weide, B.W., Harner, E. J., and Wang, L., "Tecahing Component-Based Software Engineering: A Formal Approach and Its Evaluation," *Computer Science Education*, Swets & Zeitlinger, accepted to appear.
47. Sitaraman, M., Long, T.J., Weide, B.W., Harner, E. J., and Wang, L., "A Formal Approach to Component-Based Software Engineering: Education and Evaluation," *Proceedings of the International Conference on Software Engineering (ICSE)*, IEEE, May 2001, 601-609.
48. M. Sitaraman, B. W. Weide, and W. F. Ogden, *Design, Specification, Implementation, and Analysis of Software Components*, CP SC 372 Course Notes, Clemson University, Clemson, SC 29634, 2001.
49. E. A. Addy, A. Mili, and S. Yacoub, "A Case Study in Software Reuse," *Software Quality Journal*, 2000.
50. S. Yacoub, A. Mili, C. Kaveri, and M. Dehlin, "A Hierarchy of COTS Certification Criteria", *Proceedings of the First Software Product Line Conference*, Denver, Colorado, August 2000.

51. T. J. Long, B. W. Weide, P. Bucci, and M. Sitaraman, "Client-View First: An Exodus from Implementation-Biased Teaching", *Proceedings of the Thirtieth SIGCSE Technical Symposium on Computer Science Education*, ACM Press, March 1999.
52. E. A. Addy and M. Sitaraman, "Formal Specification of COTS-Based Software: A Case Study", *Proceedings of the ACM SIGSOFT Fifth Symposium on Software Reuse*, ACM Press, May 1999, pp. 83-91.
53. T. Long, B. W. Weide, P. Bucci, D. S. Gibson, J. Hollingsworth, M. Sitaraman, and S. Edwards, "Providing Intellectual Focus to CS1/CS2," *Proceedings of the Twenty-Ninth SIGCSE Technical Symposium on Computer Science Education*, ACM Press, March 1998, pp. 252-256.
54. H. Tesser, H. Al-Haddad, S. McClaugherty, and J. Frame, "Experience with an Undergraduate Research Project: Software Reuse and Interoperability Study", *Journal of Computing in Small Colleges*, Vol. 14, No. 1, November 1998.
55. M. Sitaraman, *Introduction to Software Engineering Using Properly Conceptualized Objects*, CS 16 Course Notes, WVU Publications, 1997.

#### **C.4 Human Resource Development**

##### *Ph. D. Dissertations*

56. A. L. N. Reddy, *Formalization of Storage Considerations in Software Design*, Ph. D. Dissertation, Department of Computer Science and Electrical Engineering, West Virginia University, Morgantown, WV 26506, April 1999.
57. E. A. Addy, *Verification and Validation in Software Product Line Engineering*, Ph.D. Dissertation, Department of Computer Science and Electrical Engineering, West Virginia University, July 1999.
58. S. M. Yacoub, *Pattern-Oriented Analysis and Design (POAD)*, Ph.D. Dissertation, Department of Computer Science and Electrical Engineering, West Virginia University, October 1999.
59. D. M. Fleming, *Foundations of Object-Based Specification Design*, Department of Computer Science and Electrical Engineering, West Virginia University, Morgantown, WV 26506, 1997.
60. G. Rinard, *Performance-Tunable Distributed Execution of Object-Based Software*, Department of Computer Science and Electrical Engineering, West Virginia University, Morgantown, WV 26506, 1997.

*M. S. Theses and Reports*

- 61 M. Aronszajn, *A System for Predictable Component-Based Software Construction*, M. S. Thesis, Department of Computer Science and Electrical Engineering, West Virginia University, Morgantown, WV 26506, 2001, expected.
62. W. H. Goff, *Programming Wizards: Generating Syntax-Free Conceptual Editors*; M. S. Thesis, Department of Computer Science and Electrical Engineering, WVU, January 1999.
63. B. Markle, *Semantic Analysis of RESOLVE*, M. S. Thesis, Department of Computer Science and Electrical Engineering, WVU, January 1999.
64. X. Zhang, *Use of Intermediate Representations for Effective Multi-Source/Multi-Target Translation*; M. S. Report, Department of Computer Science and Electrical Engineering, WVU, January 1999.
65. N. Bhat, *An Exercise in Reengineering of a Database Interface*, M. S. Report, Department of Computer Science and Electrical Engineering, West Virginia University, Morgantown, WV 26506, October 1998.
66. G. Shakir, *A Systematic Generator for Interface Violation Detection in Component-Based Software*; Department of Computer Science and Electrical Engineering, WVU, August 1997.

#### **D. Participating Scientific Personnel**

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Prof. Hisham Al-Haddad (Marshall University).  
Prof. Hany Ammar (Computer Science and Electrical Engineering, West Virginia University).  
Prof. John Atkins (Computer Science and Electrical Engineering, West Virginia University).  
Dr. Paolo Bucci (Computer and Information Science, Ohio State University).  
Prof. Magdelana Bugaj (Statistics, West Virginia University).  
Prof. Donald F. Butcher (deceased).  
Mr. Naveen Bhat, received M.S., 1998.  
Prof. Jack Callahan (Computer Science and Electrical Engineering, West Virginia University).  
Prof. David M. Fleming (Concord College, WV), received Ph. D. in 1997.  
Mr. Windell Goff, received M. S., 1999.  
Prof. E. James Harner (Statistics, West Virginia University)  
Mr. Benjamin Markle, received M. S., 1999.  
Greg Kulczycki, Ph. D., 2002 (expected).  
Prof. Debbie Pittman (Bluefield College, WV).  
Dr. Yacoub Sherif, received Ph. D., 1999.  
Dr. A. L. N. Reddy (Moms Desk Commerce Corporation, CA), received Ph. D., 1999.  
Prof. George Rinard (Frostberg State University, MD), received Ph. D., 1999.  
Mr. Gulam Shakir (Parametric Corporation, FL), received, M. S., 1997.  
Mr. Chris Smith (Lockheed Martin).  
Prof. Murali Sitaraman (Computer Science, Clemson University).  
Prof. Herb Tesser (Marshall University).  
Ms. Liqing Wang (Statistics, WVU), received, M. S., 2000.  
Prof. Bruce W. Weide (Computer and Information Science, Ohio State University)  
Mr. Xiankun Zhang, received M. S., 1999.